ISSN 2816-8070

RESEARCH ARTICLE

Navigating Global Regulations for Sustainable Electronics: A Strategic Innovation Framework

Henry Efe Onomakpo Onomakpo*

Faculty of Economics and Business, Universitas Gadjah Mada, Indonesia

Abstract

The electronics sector faces growing pressure to adopt Circular Economy (CE) principles. This study explores how environmental regulations, technological innovation, and different business approaches shape this transition, aiming to provide a strategic guide. The study analyzed 78 publications from 2012-2025 using a combined literature review and bibliometric analysis from key academic databases. The findings confirm increasing research interest in this area. Environmental regulations are shown to be powerful drivers for sustainable change in the industry. Key strategies identified include designing products for sustainability, using advanced recycling methods, and adopting circular business models, such as offering products as a service. However, significant challenges remain, including inconsistent policies across regions, differences in infrastructure, and the complexity of global supply chains. Research hotspots focus on recycling, resource recovery, and the roles of various stakeholders. Based on these insights, the study proposes a conceptual framework to help develop regionally appropriate circular economy business models for managing electronic waste. This framework offers practical guidance for businesses and policymakers, emphasizing how regulations can spur innovation and why locally adapted solutions are essential for a successful circular transition, moving beyond one-size-fits-all strategies.

Key Words: *Circular economy; E-waste management; Sustainable innovation; Electronics industry; Environmental regulations*

1. Introduction

The unrelenting growth of the worldwide electronics sector poses a serious challenge: the increasing volume of abandoned equipment, sometimes known as electronic trash or e-waste [1]. This spike raises major environmental and public health issues due to the toxic compounds found in these items [2]. Additionally, improper disposal means valuable materials embedded in e-waste are often lost, representing a missed economic opportunity [3]. The traditional economic pattern of producing, using, and discarding electronics is proving unsustainable, highlighting the urgent need for circular economy models [4]. Such models prioritize waste prevention, encourage the reuse and refurbishment of products, maximize the recovery of materials through recycling, and capture energy from end-of-life items [5].

***Corresponding Author**: Henry Efe Onomakpo Onomakpo, Professor, Faculty of Economics and Business, Universitas Gadjah Mada, Indonesia; E-mail: henryonomakpo@gmail.com*

***Received Date**: March 31, 2025, **Accepted Date**: April 15, 2025, **Published Date**: May 19, 2025*

***Citation:** Onomakpo HEO. Navigating Global Regulations for Sustainable Electronics: A Strategic Innovation Framework. Int J Bank Fin Ins Tech. 2025;3(1):42-62.*

OPEN ACCESS This open-access article is distributed under the terms of the Creative Commons Attribution Non-Commercial License (CC BY-NC) (http://creativecommons.org/licenses/by-nc/4.0/), which permits reuse, distribution and reproduction of the article, provided that the original work is properly cited, and the reuse is restricted to non-commercial purposes.

Successfully shifting the electronics industry towards circularity involves integrating several key approaches. These range from designing products with circularity in mind (eco-design) [6] and employing sophisticated recycling technologies [7] to adopting business models that extend product usability [8] and strengthening producer responsibility frameworks [9]. Despite these potential solutions, considerable hurdles remain. The global nature of electronics supply chains complicates material tracking and reverse logistics [10]. Many regions lack the necessary infrastructure and data systems for effective e-waste collection and processing [11]. Furthermore, insufficient consumer engagement in take-back and recycling programs [12] and the fragmentation of policies across different countries and regions hinder progress [13].

This study synthesizes existing academic literature to illuminate the key dynamics shaping the electronics sector's transition towards a circular economy. By examining documented evidence on regulations, technological developments, business strategies, and contextual variations, we aim to map the current landscape of circular economy implementation for electronics, including its successes and limitations.

Therefore, based on a review of the existing literature, this study addresses the following core questions:

- What are the predominant circular economy strategies, regulatory influences, and key implementation challenges identified in the academic literature concerning the electronics sector and electronic waste management?
- How does the existing research characterize the role of regional context, technological advancements, and stakeholder collaboration in shaping the effectiveness of circular economy initiatives for electronics?

2. Materials and Methods

This study employed a mixed-methods approach, combining a systematic literature review (SLR) with a bibliometric analysis, to explore the complexities of transitioning to a circular economy in the electronics industry.

2.1. Data sources and search strategy

The SLR followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [14], as illustrated in Figure 1. The search strategy was formulated to identify relevant publications focusing on circular economy, sustainable innovation, e-waste management, and the electronics industry. An initial search was conducted in the Scopus, Web of Science (WoS), and Dimensions databases, yielding 1077 publications. The search terms are (Circular economy or Sustainable innovation) and (Electronics industry or E-waste management) and (WEEE or Eco-design Directive or 9R framework).

The study employed inclusion criteria requiring publications to be peer-reviewed journal articles, book chapters, or conference proceedings focused on the electronics industry and e-waste management. Inclusion was further limited to publications in English, primarily due to the research team's language capabilities and the resource constraints associated with accurately translating and interpreting technical literature from multiple languages. It is acknowledged that this criterion may introduce a potential bias by excluding relevant studies published in other languages, potentially underrepresenting perspectives from certain

geographical regions or research communities. After applying these inclusion criteria, 159 publications were retained. Subsequently, articles that were not relevant to the study topic were removed, leaving 87 publications. Finally, duplicate entries were removed, resulting in a final set of 78 publications for the SLR.

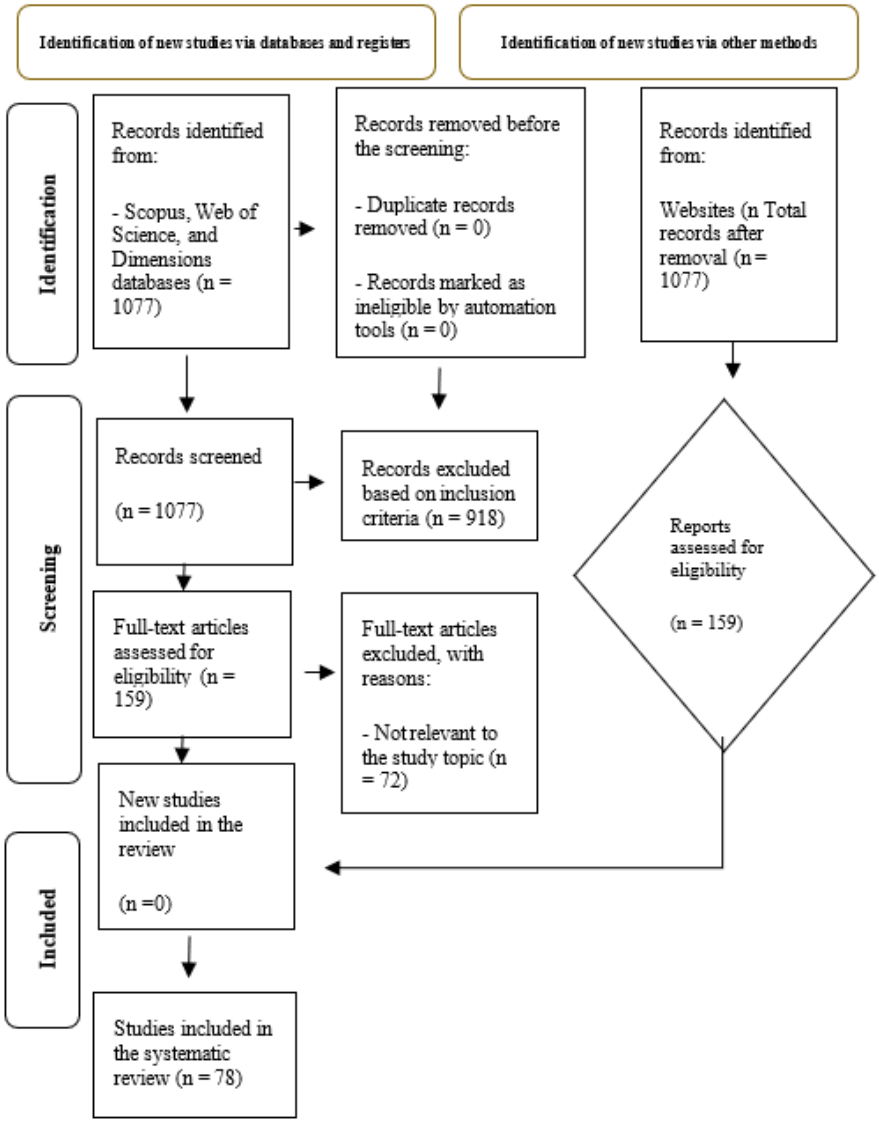
Identification of new studies via databases and registers
Identification of new studies via other methods
Identification
Records identified from:
- Scopus, Web of Science, and Dimensions databases (n = 1077)
Records removed before the screening:
- Duplicate records removed (n = 0)
- Records marked as ineligible by automation tools (n = 0)
Records identified from:
Websites (n Total records after removal (n = 1077)
Screening
Records screened
(n = 1077)
Records excluded based on inclusion criteria (n = 918)
Reports assessed for eligibility
(n = 159)
Full-text articles assessed for eligibility (n = 159)
Full-text articles excluded, with reasons:
- Not relevant to the study topic (n = 72)
Included
New studies included in the review
(n =0)
Studies included in the systematic review (n = 78)

Figure 1: *PRISMA diagram of search strategy. The diagram illustrates the systematic review process, detailing records identified, screened, assessed for eligibility, and included in the final analysis. Data sources include Scopus, Web of Science, and Dimensions.*

2.2. Bibliometric analysis

To gain a quantitative overview of the field, bibliometric analysis was performed using a combination of tools. R's Bibliometric package and Bibliophagy library were utilized for data extraction, cleaning, and processing. VOS viewer was employed to enhance visualization of the key trends, emerging topics, and collaborative networks within the literature. The combined insights from the SLR and the bibliometric analysis formed the basis for the development of a conceptual framework to guide future research and action.

The bibliometric analysis, summarized in Table 1, of 78 publications concerning e-waste and the circular economy from 2012 to 2025 across 57 sources, demonstrates a field with an annual growth rate of 5.48% and an average document age of 3.46 years, in which articles represent the largest portion of publications and have received on average 25 citations per document, indicating a sustained and relatively recent area of scholarly focus. Collaborative characteristics include an average of 4.28 authors per document and 23% international co-authorships among the 319 authors.

Table 1: *Bibliometric overview of dataset - key metrics and descriptive statistics.*

Description	Results
Documents	78
Timespan	2012:2025
Sources (Journals, Books, etc.)	57
Annual Growth Rate %	5.48
Document Average Age	3.46
Average citations per doc	25.15
References	0
Keywords Plus (ID)	42
Author's Keywords (DE)	42
Authors	319
Authors of single-authored docs	4
Single-authored docs	4
Co-Authors per Doc	4.28
International co-authorships %	23.08
Article	59

2.3. Ethical considerations

This study is based on published scholarly articles. Therefore, no ethics committee approvals were needed.

2.4. Study limitations

Several limitations should be considered when interpreting the findings of this study. Firstly, potential selection bias might exist due to the specific search strategy and keywords used, potentially omitting some relevant studies. Secondly, the databases used (Scopus, Web of Science, Dimensions), while comprehensive, do not encompass all existing literature. Thirdly, as noted in the inclusion criteria, restricting the analysis to English-language publications may exclude valuable research and perspectives from non-English-speaking regions. Furthermore, the focus on peer-reviewed publications means that insights from 'gray literature'—such as industry reports, government policy documents, white papers, or dissertations—were largely excluded. This exclusion, while ensuring a focus on academically vetted research, might limit the incorporation of practical, real-world implementation details, industry-specific data, or very recent policy developments not yet captured in scholarly journals.

Similarly, non-peer-reviewed sources like preprints or conference presentations without formal proceedings were not included, potentially delaying the capture of the most nascent research trends, although this approach strengthens the study's grounding in validated findings.

3. Results

This section focuses on discoveries from the 78 selected publications on e-waste management. The study will ensure an in-depth analysis of findings from the literature review and bibliometric analysis to derive valuable insights.

3.1. Literature review

The systematic literature review highlights the complex interplay between environmental regulations, technological innovation, and business models in the transition towards a circular economy in the electronics sector. The findings provide insight into how various regulatory interventions and innovative strategies can contribute to a more sustainable and resource-efficient industry.

3.1.1. Environmental regulations and innovation

Environmental regulations are vital for fostering sustainable innovation and guiding e-waste management practices. Policies such as the EU's Eco-design Directive and Extended Producer Responsibility (EPR) schemes have significantly influenced producers to adopt more sustainable approaches [15]. For instance, regulations focused on electronic product design [6,16] have prompted manufacturers to prioritize recyclability and material composition. Research indicates that environmental regulations stimulate stakeholder networks for both the creation and dissemination of technical and managerial innovations [17]. Moreover, effective collaboration among governments, businesses, and civil society organizations can build trust and cooperation, which are essential for achieving long-term [18]. The analysis also highlights a growing need to expand producer responsibility through the adoption of eco- design strategies [19]. International collaborations are also critical for promoting recycling and preventing the illegal e-waste trade [20], serving as a key strategy for harmonizing circular economy principles with eco-sustainability goals [2].

3.1.2. Beyond the linear: embracing circular business models

A transition to a circular economy demands a departure from traditional linear business models, favoring innovative approaches that prioritize resource efficiency and waste reduction. This shift is evident in the adoption of Circular Business Models (CBMs) such as product-as-a-service, product-sharing platforms, and strategies for extending product lifecycles [21]. These models emphasize repair, reuse, and remanufacturing [22] to reduce reliance on virgin materials and extend the useful life of electronic products. Moreover, new business models are emerging that create value streams from electronic waste [23]. However, the implementation of circularity in the electronics sector faces several [8], requiring the establishment of a supportive environment for circular economy models to thrive [15] and the active engagement of consumers in the circularity of products [24,25].

3.1.3. Sustainable innovation in practice: success from the ground up

Successful e-waste management hinges on the development of novel processes and techniques for effective material reuse, recycling, and recovery [26]. Numerous studies are exploring the use of bioleaching and bio cyanide methods [3] to improve resource recovery. Emerging technologies, such as augmented reality (AR) systems, are also playing a role in improving e-waste recycling processes, facilitating the identification and separation of recyclable materials [27], and promoting circular supply chains [28].

Simultaneously, promoting decentralized and localized material recycling [4], adopting more efficient and cost-effective technologies [29], and integrating the informal sector into e-waste management processes are crucial steps [30]. Finally, accurate data tracking [11] and material transparency and traceability throughout the supply chain [9] are essential.

Blockchain technology can also enhance transparency, reduce transaction costs, and encourage sustainable e-waste management practices [31,32]. Furthermore, there is a recognized need for improved environmental management systems and a greater understanding of CE practices among all stakeholders [5,33].

3.2. Quantitative findings on scientific production, influential authors, and geospatial analysis

The examination of the scholarly output on e-waste and the circular economy reveals trends in scientific production, highlights influential contributors and suggests a geographic distribution of research emphasis, which are instrumental in shaping a framework for innovation in the circular economy.

3.2.1. Scientific output over time

The analysis of publication trends, presented in Table 2, demonstrates a fluctuating but generally increasing interest in this research area over the last decade (2012-2025). There were no publications between 2013 and 2015, but this changed drastically in 2017, where the top mean total citations per article (80.8) and per year (8.98) were registered, followed by 2021, indicating a shift from an initial period of low activity to a more sustained period of scholarly investigation that peaked in 2023 (20 articles) (Table 2).

Notably, publication frequency has generally increased, peaking in 2023 with 20 publications. The mean total citation per article and year varied significantly across the years (Table 2). However, the most recent years show a lower average of citations per year, which indicates an emerging trend. These findings highlight the increasing importance of this field and a developing understanding of e-waste and the circular economy.

Table 2: *Average scholarly output and citation impact - average citations and citation longevity.*

Year	Articles	MeanTCperArt	N	MeanTCperYear	CitableYears
2012	1	11	1	0.79	14
2013	0	0	0	0	0
2014	0	0	0	0	0
2015	0	0	0	0	0
2016	1	82	1	8.2	10
2017	5	80.8	5	8.98	9
2018	3	41.33	3	5.17	8
2019	3	43	3	6.14	7
2020	7	28.29	7	4.72	6
2021	10	49.6	10	9.92	5
2022	14	22.21	14	5.55	4
2023	20	9.1	20	3.03	3
2024	12	2.08	12	1.04	2
2025	2	0	2	0	1

Articles = The total number of articles published in the given year, MeanTCperArt = The average total citations per article for the year, N = The number of articles considered in the calculation for that year, MeanTCperYear = The average citations per year for the articles published in that year, Citable Years = The number of years the articles from that year have been citable or available for citation.

3.2.2. Influential sources and authors

The analysis of relevant sources, as shown in Table 3, identifies certain journals as key contributors to the field. The Journal of Cleaner Production (8 articles) and Sustainability (7 articles) are the most frequently cited sources. Other journals and book series, including Resources, Conservation and Recycling, Environmental Science and Pollution Research, and The Science of the Total Environment, along with conference proceedings such as 2024 Electronics Goes Green 2024+ (EGG), 2023 9th International Conference on Advanced Computing and Communication Systems (ICACCS), and 2023 IEEE International Conference on Blockchain and Cryptocurrency (ICBC), also play a significant role in disseminating related research (Table 3).

Notably, several publications in Sustainability and the Journal of Cleaner Production focus on strategies for promoting a circular economy for e-waste through reverse chain analysis and highlight effective e-waste management systems and practices [34,35]. These publications also examine consumer behavior related to WEEE, specifically concerning circular or transformational practices [24].

Table 3: *Distribution of articles on e-waste management across top scientific sources.*

Sources	Articles
Journal of cleaner production	8
Sustainability	7
Resources conservation and recycling	4
2024 Electronics goes green 2024+ (Egg)	2
Clean technologies and environmental policy	2
Environmental science and pollution research	2
The science of the total environment	2
Waste management & research the journal for a sustainable circular economy	2
2023 9th International conference on advanced computing and communication systems (ICACCS)	1
2023 Ieee international conference on blockchain and cryptocurrency (ICBC)	1

Sources = These refer to the journals, conferences, or other outlets where the articles related to your research topic were published, articles = this column lists the number of articles from each source.

3.2.3. Most productive authors

Table 4 identifies authors who have been particularly active in the e-waste and circular economy domain, with key contributors like Amorim, M and Tucci, HNP contributing 3 publications each.

Table 4: *Top contributing authors in e-waste management research: publication count and fractional authorship.*

Authors	Articles	Articles fractionalized
Amorim M	3	0.57
Tucci HNP	3	0.57
Aguilar-Barajas I	2	0.5
Babbitt CW	2	0.58
Cordova-Pizarro D	2	0.5
Correia AJC	2	0.37
Marujo LG	2	0.45
Rodrigues Fl	2	0.37
Rodriguez CA	2	0.5
Romero D	2	0.5
Senna P	2	0.45
Singh S	2	0.5
Xavier LH	2	0.83

Authors = The names of the authors who contributed to the publications, Articles = The total number of articles published by each author, Articles Fractionalized = The fractional contribution of the author to the articles, based on co-authorship. This accounts for the share of authorship, ensuring proportional credit when multiple authors are involved. For example, if an article has three authors, each might receive a fractional contribution of 1/3.

The work of authors such as Babbitt, CW, Cordova-Pizarro, D, Romero, D, and Rodriguez CA has been instrumental in analyzing material flow and identifying challenges within the e-waste stream [36,37]. The involvement of authors such as Senna, P, shows a dedication to exploring supply chain dynamics for e-waste [38]. These authors have helped define the key challenges and opportunities within this field.

3.2.4. Geospatial emphasis

Although a detailed geospatial analysis was not explicitly undertaken, the affiliations of contributing authors, as detailed in Figure 2, evidently reveal a heterogeneous distribution of research activity. Predominantly, countries such as Brazil, India, and China ostensibly demonstrate a higher number of publications in the field, arguably indicating a focused research effort in these regions. Conversely, other regions, including Australia, several European countries, and the USA, show a moderate presence. Furthermore, although other countries display some research activity, most contributions were Single-Country Publications (SCP) when juxtaposed to the Multiple-Country Publications (MCP), indicating an initial phase of collaborative efforts (Figure 2). This international spread, while purportedly diverse, inevitably highlights the global nature of the e-waste challenge and fundamentally emphasizes the need for a common approach within the framework, which must draw from diverse key players that are practically working to improve the e-waste sector.

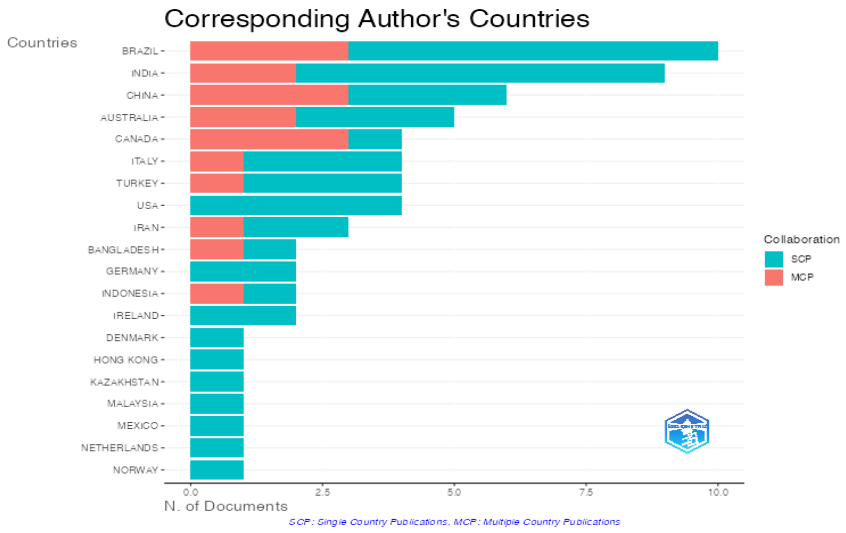

Figure 2: *Geographic distribution and collaboration patterns in e-waste management research: a country-level analysis.*

Source: *Data compiled by the author from the Scopus database were analyzed using the R package bibliometrix.*

3.2.5. Keyword analysis and circular economy solutions for WEEE management

The keyword analysis, as depicted in Figure 3, offers nuanced perspectives on the predominant themes within research on the circular economy and e-waste management. The frequent appearance of terms such as recycling, waste management, and electronic waste, ostensibly highlights a substantial focus on these fundamental elements of e-waste management. Meanwhile, terms including solid waste, refuse disposal, and soil pollutants unremittingly underscore the environmental impacts associated with e-waste and the inherent demand for appropriate handling methods. Furthermore, the occurrence of terms

such as metals, metals, heavy, metals, rare earth, lithium, cobalt, and neodymium explicitly reveals a clear understanding of the material recovery possibilities within e-waste [3,26,39] and the fundamentally significant role they effectively play in the e-waste management sector. Consequently, these findings suggest the importance of ongoing research focused on material recovery and resource efficiency within a circular economy framework. The inclusion of geographically significant terms, such as China, Brazil, Australia, Germany, Italy, Romania, Sweden, and Turkey, illustrates the inextricable nature of the global context within e-waste management. Alternatively, the European Union purportedly indicates the

influence of its policy measures in this specific area [40,41]. Moreover, the presence of terms such as humans, consumer behavior, and probability invariably emphasizes that successful implementation of circular models necessarily requires an understanding of public perceptions and the importance of stakeholder engagement. Furthermore, terms such as heterotrophic processes, technology, and environmental monitoring arguably highlight the role of emerging technologies [42], biological processes [3], and enhanced monitoring protocols as crucial factors in innovation in this field. Finally, terms such as game theory, models, economic, models, theoretical, and uncertainty demonstrate the need for robust frameworks to support informed decisions when designing effective e-waste management strategies.

Figure 3: *Frequency distribution of key terms in e-waste management research.*

Source: *Data compiled by the author from the Scopus database were analyzed using the R package bibliometrix.*

3.2.6. Co-word network analysis and circular economy solutions for WEEE management

The co-word network analysis presented in Figure 4 provides detailed insights into the key themes emerging from research on the circular economy and WEEE management. The frequent co-occurrence of terms such as e-waste, waste, management, circular, electronics, and economy underscores the significant interconnections between these concepts. It suggests that a comprehensive understanding of electronic waste, waste, and management is essential for the effective implementation of the circular economy model. The high betweenness centrality of terms like waste, management, circular, and electronic identifies them as pivotal connectors within the network, highlighting their crucial roles in the framework for WEEE. This indicates that much of the relevant research focuses on developing circular models for improved waste management. Conversely, several less frequently mentioned terms also play important roles in this field.

Terms with high closeness centrality, such as e-waste, waste, management, circular, electronic, and economy, clearly indicate that these concepts are closely related and form the foundation of current discussions. PageRank scores, which measure relative influence, identify terms like recycling, waste, management, circular, and economy as the most significant within this domain (Figure 4). These findings emphasize that any framework aiming for circularity must consider these interconnected components.

Additionally, smaller yet influential clusters are evident. The group comprising environmental, equipment, sustainable, electronics, electrical, countries, research, and development highlights the significance of broader sustainability contexts and the ongoing need for research and development in this sector. Other clusters emphasize the importance of terms such as reuse, analysis, paper, industry, sustainability, and practices, which point to the necessity of innovative solutions that include reuse and sustainable practices. The role of various strategies, including data, systems, consumer, approach, and chain, in creating effective circular models is reflected in terms like supply, recovery, technologies, recycling, products, study, materials, challenges, review, literature, potential, global, implementation, product, and critical, aligning with the broader trend towards a circular economy.

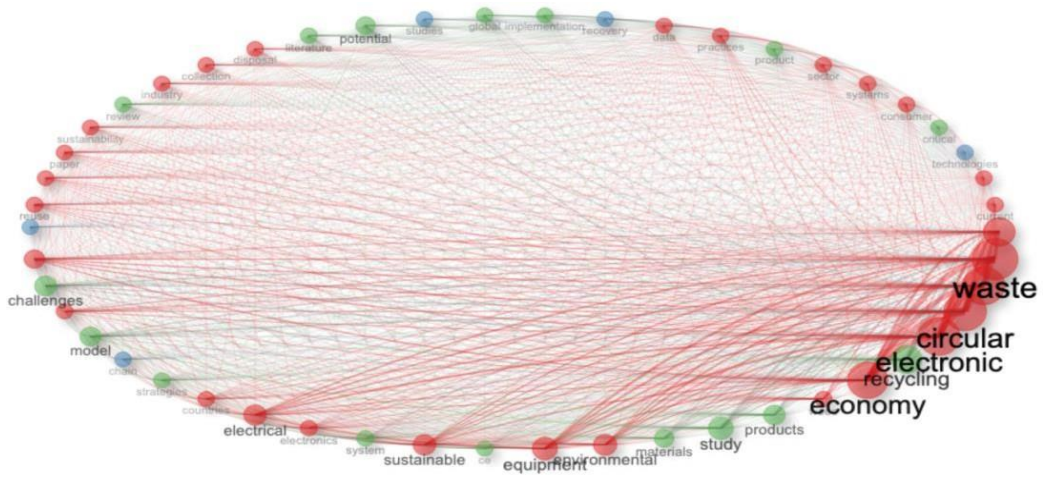

Figure 4: *Most relevant words. This figure presents the key concepts in e-waste management research: cluster, centrality, and importance metrics.*

Source: *Data compiled by the author from the Scopus database were analyzed using the R package bibliometrix.*

4. Discussion

This section synthesizes the insights from the literature review, the keyword analysis, and the co- word network analysis to discuss key elements that can inform the development of a circular economy business model framework for Waste Electrical and Electronic Equipment (WEEE).

Addressing RQ1: Stakeholder Roles and Collaboration in AI-Integrated E-Waste Management. Analysis of influential publications (Table 3), such as those in the Journal of Cleaner Production and Sustainability, reveals a strong focus on policy frameworks and innovative business models as crucial levers for managing e-waste. The prominence of authors like Amorim M, Tucci HNP, and Aguilar-Barajas I in these journals (Table 4)

underscores research efforts aligned with these themes. For instance, studies often examine the effectiveness of Extended Producer Responsibility (EPR) schemes, highlighting the critical role of manufacturers (as primary stakeholders) in funding and organizing collection and recycling [19].

Successful implementation, however, demands more than just manufacturer compliance; it requires active collaboration. Consider the WEEE Forum, a prominent example of collaboration where producer responsibility organizations across Europe share best practices and data.

Integrating AI further complicates stakeholder roles. AI developers become key stakeholders, needing to collaborate with recyclers to ensure algorithms are trained on relevant waste streams and material compositions. Governments, as regulators, must create data governance frameworks for AI use, ensuring privacy and fair access. Enhanced collaboration, potentially facilitated by shared data platforms (perhaps utilizing blockchain for trust), is therefore crucial for implementing advanced, AI-driven technologies effectively and addressing diverse stakeholder needs within complex e-waste management systems.

4.1. Insights for the circular economy business model framework

The identified trends in scientific output, leading sources, and influential authors effectively highlight a clear pathway for a robust circular economy framework. This framework must fundamentally emphasize compliance with regulations while simultaneously promoting innovation and generating value.

4.1.1. Regulations as drivers of innovation

Regulations undeniably play a crucial role in stimulating innovation within e-waste management, recycling, and eco-design [6,9,19]. For example, the EU's Eco-design Directive has pushed manufacturers like Fairphone to develop modular smartphones designed for easier repair and component replacement, directly fostering innovation in product longevity. However, to achieve full effectiveness, regulatory frameworks must foster collaboration across the value chain [18] such as partnerships between manufacturers and recyclers to ensure designs align with existing recycling capabilities and guarantee the implementation of new technologies [12]. Consequently, well-designed regulations can incentivize stakeholders to transition to circular models.

Business models embracing circularity are important for waste reduction and increasing recycling rates [21]. Examples include 'Product-as-a-Service' models, where companies like Signify (formerly Philips Lighting) retain ownership of lighting fixtures, offering illumination as a service and managing end-of-life recovery. These models can enhance profitability and competitive advantage [15]. Companies creating value through recycling, remanufacturing (e.g., Caterpillar's remanufacturing program for heavy equipment components, though not electronics, illustrates the potential), and sustainable product development, coupled with transparent supply chains (perhaps using blockchain to track conflict minerals) and advanced technologies (like AI-optimized sorting or AR-assisted disassembly identified by Sureshkumar, et al. [27], can gain competitive advantage, meet [31], and contribute to Sustainable Development Goals [43].

Innovation is essential to overcome compliance challenges like limited recycling capacity, high costs, and deficient infrastructure [29,37]. For instance, innovations in robotic sorting using AI and computer vision are helping automate the separation of complex e-waste streams, potentially reducing costs and improving material purity. Innovative approaches to reverse logistics (e.g., optimizing collection routes with AI based on predicted fill levels of e-waste bins), material recovery (such as advancements in hydrometallurgy for reclaiming critical metals), new business models (e.g., refurbishment platforms like Back Market), and sustainable materials [44,45] are crucial.

4.2. Circular economy business model framework insights

The keyword analysis highlights the need to prioritize innovation and the 9Rs (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle) in the transition to circular models for WEEE. Literature analysis [16,40] demonstrates the fundamental importance of regulatory frameworks, policies, and economic viability. Policy and legislation from developed nations are essential drivers for innovative business models.

The recurring use of terms like recycling, recovery, materials, products, and system, alongside reuse, underscores the importance of resource recovery and value creation. A successful framework must prioritize these components and consider the economic feasibility of material recovery [3,26,39]. This involves assessing the cost-effectiveness of recovering specific metals versus virgin material prices or evaluating the market demand for refurbished versus new products.

Ultimately, e-waste management must generate value through efficient recycling, appropriate refuse disposal, and the recovery of valuable metals, potentially using advanced biological methods (heterotrophic processes). Innovative business models promoting circularity are essential for human well-being and ecosystem protection.

4.3. Conceptual framework for circular economy in e-waste management

Figure 5 outlines an integrated, circular approach to e-waste management, highlighting the interconnectedness of design, consumption, end-of-life management, continuous improvement, and stakeholder collaboration. This framework integrates key aspects of design, consumption, end-of-life management, continuous improvement, and stakeholder collaboration, forming a dynamic and adaptable system that incorporates feedback loops for continual optimization. This central core, depicted in Figure 5, is the foundation of the framework and shows a circular flow organized in three interconnected quadrants. The initial quadrant, which is the Sustainable Design and Production, addresses the inherent design and manufacturing processes for electronic products.

The Sustainable Design and Production, input requires Regulated Design & Materials Choices [16]. Emphasizes eco-design principles (durability, modularity, disassembly, material selection) [4]. Output includes products easier to repair, reuse, and recycle [12], reducing raw material demand. AI could assist here by simulating disassembly processes or recommending materials based on regional recycling infrastructure. Meanwhile, the Responsible Consumption and Use Input emphasizes Transparent Supply Chains using blockchain for verifiable tracking of materials like cobalt or rare earths [31,32], and eco-labels. Promotes repair, refurbishment, reuse, product sharing, and take-back programs [36]. Output includes extended

product life, reduced demand, enhanced consumer engagement (Khan et al., 2023), and supporting reuse, repair, refurbish, repurpose (9Rs).

Whereas, the Value Capture through Effective End-of-Life Management Input requires robust Effective Collection Systems [46]. The process uses optimized logistics, dismantling, sorting, and testing, potentially using AI-based visual recognition systems for component identification or robotic arms for disassembly [22,27]. Secure disposal of hazardous substances is key. Output is the recovery of materials, remanufacturing parts, and secure disposal [40], transforming "waste" into products. Drawing from the Conceptual Framework (Figure 4) to address RQ2: The framework illustrates how AI and related technologies integrate across stages.

For Sustainable Design, AI analyzes material properties and supply chain data to suggest designs optimized for recyclability within specific regional capabilities (e.g., recommending easily separable plastics if advanced chemical recycling isn't locally available). AI can also predict product lifespan under different usage scenarios to inform design robustness.

Furthermore, AI can power consumer-facing apps that identify product materials, provide repair guides, or locate nearby collection points. Blockchain provides immutable proof of a product's journey and material content, enhancing transparency and consumer trust, potentially linked via QR codes on products. The End-of-Life Management sees a direct AI impact. AI-driven optical sorters (using cameras and hyperspectral imaging) achieve higher purity rates for plastics and metals. Predictive analytics optimize e-waste collection routes based on historical data and potentially smart bin sensors. Robots guided by AI can automate hazardous disassembly tasks, like battery removal. Ultimately, synthesizing literature review insights depicts innovation drives AI adoption to overcome barriers like limited recycling capacity or high costs [29,37,44]. For example, where manual sorting is too costly or inefficient for complex e-waste, AI robotics offers a viable alternative.

4.3.1. Key enablers: driving forces for a successful framework:

Positioned around the core circular flow are key enablers that act as driving forces for the entire system. The Compliance Regulations and Policy Support section represents the external drivers that guide the e-waste management sector. This includes policies and regulations that promote sustainability and that can support a transition to a circular economy [15], as shown by the presence of the WEEE Directive, REACH, the Eco-design Directive and global standards. Moreover, the inclusion of governmental incentives will ensure that all parties engage in eco-design practices, promote R&D and adopt circular business models. The main aim of this is to guarantee adherence to all levels of regulations while also promoting a shift toward sustainable objectives.

Meanwhile, the Firms Leveraging Regulations for Market Differentiation and Competitive Advantage element emphasizes that strategic implementation of regulations is inherently a pathway to achieve a competitive advantage. By adopting certifications, embracing eco-labelling, and building consumer trust, companies are establishing a better position in the market [15]. As supported by existing research, firms can use compliance to build their brand and attract environmentally conscious consumers [24,25]. The Overcoming Compliance Challenges through Innovation section explicitly highlights the role of continuous research and development is crucial for cost reduction, enhancing material recovery (e.g., developing selective leaching processes for specific metals), addressing resource limits, and creating new business models [44]. Next is the Stakeholder Collaboration and Transparency section, which

emphasizes the need for a collaborative approach among all actors in the value chain, such as producers, recyclers, consumers, governments, and research institutions [29]. Transparency enabled by technologies like blockchain builds trust by providing auditable records of material flows and compliance [31,32].

Figure 5, which embodies the conceptual framework, does more than simply outline a process; it intrinsically incorporates a series of innovations that are designed to improve the framework. The Innovation and Improvement Loops quadrant provides a channel for continual learning, adaptation, and optimization, based on data analysis and performance evaluation. To integrate all enablers, this framework makes use of compliance, innovation, stakeholder collaboration, and transparency to support every phase and shows that a successful framework has to address the technical, social and organizational aspects. The use of regulations for competitive advantage shows the framework is aimed at promoting sustainable choices, which in turn will enhance market positions for companies that fully embrace circular economy business models. Ultimately, the framework underscores the use of technology to achieve higher levels of material recovery, helping ensure a balance between economic viability and sustainability.

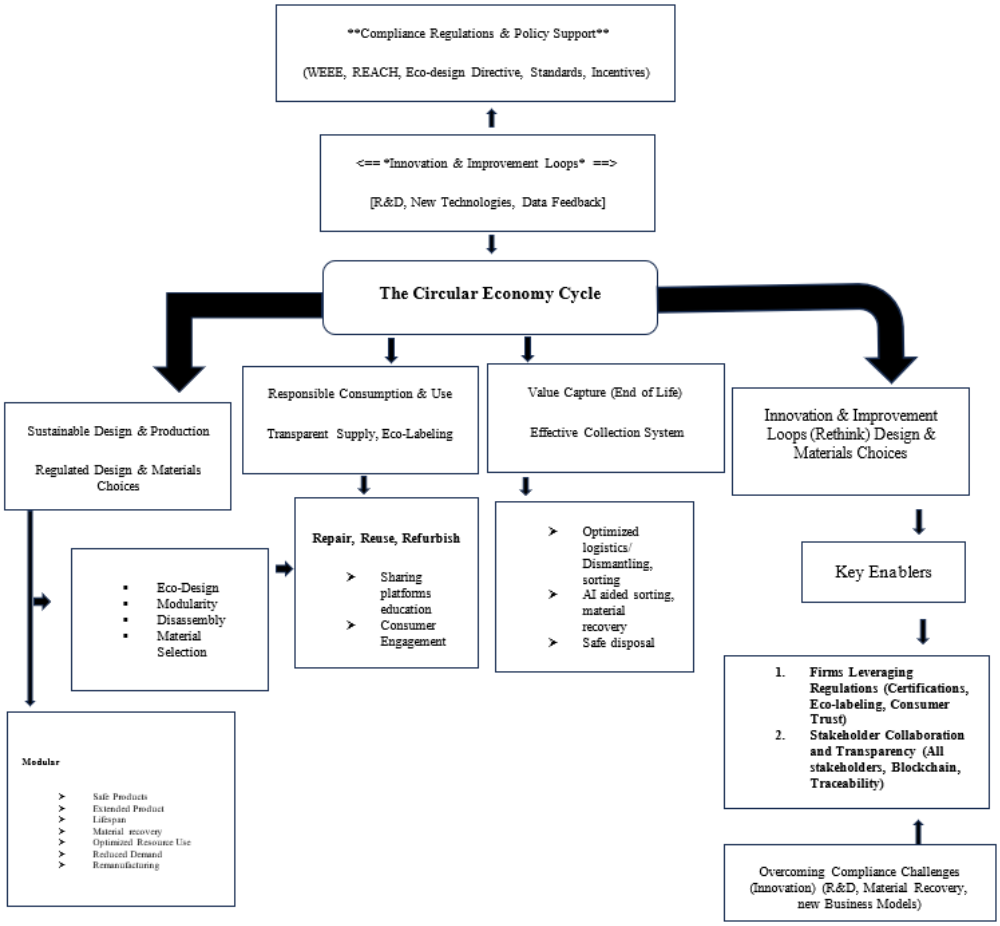

Figure 5: *Conceptual framework for circular economy in e-waste management. An integrated approach to sustainable design, consumption, and end-of-life management.*

To answer RQ2, it is evidenced that the impact of AI integration on e-waste management varies significantly across different regions due to differing economic, regulatory, infrastructural, and societal contexts. A generalized positive or negative statement is insufficient; a nuanced understanding is crucial.

In economically developed regions with robust financial and technological infrastructure (e.g., parts of Europe, North America, and East Asia), AI-driven solutions can be more readily implemented. This includes AI-powered sorting systems for efficient material recovery, predictive analytics to optimize collection logistics, and AI-enhanced eco-design to minimize waste generation at the product design stage. However, the type of economic model in place (e.g., state-directed vs market-driven) can further influence the AI application (e.g., state-directed may prioritize centralized large-scale AI systems).

Regions with stricter environmental regulations and extended producer responsibility (EPR) schemes (e.g., the European Union) are more likely to incentivize the adoption of AI-based e-waste management solutions. The Eco-design Directive pushes for more recyclable products from the start, while AI-powered sorting and collection systems can increase EPR efficiency in practice. AI then becomes an economic necessity to meet regulatory requirements efficiently. In regions with weaker regulations, AI adoption may be driven primarily by cost savings or market competitiveness. Meanwhile, in developing countries, limited access to reliable data, computing power, and skilled personnel may hinder the effective deployment of sophisticated AI systems. In these contexts, AI applications may be more focused on simpler tasks, such as improving informal waste collection systems through route optimization or providing basic material identification support using augmented reality (AR) apps, as suggested by Sureshkumar, et al. [27]. AI solutions must also integrate and respect the already established social infrastructure of these regions with inclusive and sustainable practices.

Moreover, the efficacy of AI in e-waste management hinges on access to large, high-quality datasets. Regions with robust data collection and management infrastructure are better positioned to leverage AI for predictive modeling, material flow analysis, and supply chain optimization. Conversely, in regions with limited data availability, AI applications may be constrained by data scarcity and biases, hindering accurate analysis and effective decision-making. In any case, transparency in the collection and the accessibility for those who do not have such reliable access must be protected.

In addition, consumer awareness and engagement with responsible e-waste disposal practices also play a critical role. AI-powered solutions can be used to educate consumers about proper recycling procedures, incentivize participation in take-back programs, and personalize e-waste management services. This could include gamification of recycling or apps that allow users to easily schedule e-waste pickup. In regions with low awareness, public education campaigns and community-based initiatives may be necessary to promote AI adoption and maximize its effectiveness.

Ultimately, the composition of e-waste differs regionally. Some regions produce more specific items. AI implementation should be adaptable to the regional needs of this type of e-waste. Consequently, the integration of AI into e-waste management is not a one-size-fits-all solution. Its impact depends heavily on the specific regional context, the interplay of economic, regulatory, infrastructural, and societal factors, and the accessibility of reliable data. Effective AI implementation requires a localized, adaptive, and multi-stakeholder approach that addresses the unique challenges and opportunities in each region.

5. Conclusion

This review synthesizes the complex landscape of the circular economy transition within the electronics sector, concluding that success hinges on moving beyond generic 'best practices' towards meticulously crafted, context-specific solutions. Our analysis of the literature confirms that while environmental regulations are potent drivers of innovation and specific strategies like eco-design, advanced recycling, and circular business models are crucial, their effectiveness is fundamentally shaped by regional variations in infrastructure, policy harmonization, and stakeholder engagement.

The key contribution of this study is the development of a conceptual framework (Figure 5) designed to navigate these complexities. It highlights the necessity of integrating regulatory compliance, technological innovation (including adaptable deployment of tools like AI and blockchain), and multi-stakeholder collaboration within a regionally sensitive approach. This framework builds upon existing circular economy models by explicitly emphasizing regional adaptation, a factor sometimes under-addressed in more generalized approaches. Furthermore, while the literature broadly supports the positive impact of regulations and innovation, it presents occasionally inconclusive or conflicting evidence regarding the universal effectiveness of specific interventions (e.g., certain business models or technologies) across vastly different socio-economic contexts, further reinforcing the need for tailored solutions. For policymakers, the findings underscore the need to design flexible regulatory frameworks that encourage innovation while accounting for regional capabilities. One-size-fits-all mandates are likely insufficient. Policies should actively foster collaboration across the value chain and potentially support the development of the data infrastructure needed for advanced tracking and management systems.

For industry stakeholders, businesses must strategically adopt circular practices appropriate to their operating context, leveraging regulatory requirements for competitive advantage and market differentiation. This involves investing in adaptable technologies, pursuing transparent supply chains, and actively engaging with consumers and recycling partners to close material loops effectively. It is important to acknowledge this study's limitations, including its reliance on published academic literature (potentially introducing language bias and excluding insights from gray literature) and the specific databases searched. Ultimately, achieving a truly sustainable and competitive circular economy for electronics requires a localized, adaptive, and collaborative strategy. Concentrating future research and practical implementation efforts on such tailored frameworks, informed by real-world evidence and addressing the specific challenges identified within diverse regions, is vital for navigating the inherent complexities and realizing the full potential of circularity in this critical global sector.

6. Conflict of Interest

The author declares that there are no known conflicts of interest associated with this publication, and there were no financial, commercial, legal, or professional relationships that could influence or bias the research.

7. Author Contributions

Henry Efe Onomakpo Onomakpo conceived and designed the study conducted the literature review, performed the bibliometric and content analysis, developed the integrated framework, and led the writing and revision of the manuscript.

8. Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. All activities contributing to this work were conducted using the resources of the author's institution.

9. Acknowledgments

The author gratefully acknowledges the support of the faculty and staff of the Economics and Business Department of the University of Gadjah Mada for their invaluable assistance in the preparation of this manuscript. Their guidance and encouragement were instrumental in the successful completion of this research.

10. Data Availability Statement

The bibliometric data analyzed in this study originates from the Scopus, Web of Science, and Dimensions databases. Due to the proprietary nature of these databases, direct access to the raw data is subject to individual subscription agreements with the respective database providers. However, the processed data, along with the analytical code used in this study (primarily utilizing the "bibliometrix" package in R), is deposited in the Open Science Framework (OSF) and can be accessed freely at the publisher's website. The materials will remain archived permanently.

References

1. Barapatre S, Rastogi M. E-waste management: a transition towards a circular economy. Handbook of Solid Waste Management. Springer, Singapore. 2021.

2. Zhang Z, Malik MZ, Khan A, et al. Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco- sustainability. Sci Total Environ. 2022;807:150856.

3. Golzar-Ahmadi M, Bahaloo-Horeh N, Pourhossein F, et al. Pathway to industrial application of heterotrophic organisms in critical metals recycling from e-waste. Biotechnol Adv. 2024;77:108438.

4. Dumée LF. Circular materials and circular design—review on challenges towards sustainable manufacturing and recycling. Circ Econ Sustain. 2022;2:9-23.

5. Ayçin E, Kaya SK. Towards the circular economy: analysis of barriers to implementation of Turkey's zero waste management using the fuzzy DEMATEL method. Waste Manag Res. 2021;39:1078-89.

6. De-Azua-Lahidalga IR, Valor EM, Lozano DJ, et al. Circular power electronics: exploring the scope and suitability of ecodesign criteria for the power electronics industry. Electronics Going Green 2024+, Berlin, Germany. 2024.

7. Iqbal A, Akhter S, Mahmud S, et al. Empowering the circular economy practices: lifecycle assessment and machine learning-driven residual value prediction in IoT-enabled microwave oven. Heliyon. 2024;10:e38609.

8. Williams ID, Shittu OS. Development of sustainable electronic products, business models and designs using circular economy thinking. Detritus. 2022;21:45.

9. Li K, Qin Y, Zhu D, et al. Upgrading waste electrical and electronic equipment recycling through extended producer responsibility: a case study. Circular Econ. 2023;2:100025.

10. Cicerelli F, Ravetti C. Sustainability, resilience and innovation in industrial electronics: a case study of internal, supply chain and external complexity. J Econ Interact Coord. 2023;19:343-72.

11. Dias P, Palomero J, Cenci MP, et al. Electronic waste in Brazil: generation, collection, recycling and the covid pandemic. Clean Waste Syst. 2022;3:100022.

12. Jayasiri G, Herat S, Kaparaju P. Repair and reuse or recycle: what is best for small WEEE in Australia? Sustainability. 2024;16:3035.

13. Cheshmeh ZA, Bigverdi Z, Eqbalpour M, et al. A comprehensive review of used electrical and electronic equipment management with a focus on circular economy-based policy-making. J Clean Prod. 2023;389:136132.

14. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. PLOS Medicine. 2021:18:e1003583.

15. Fetanat A, Tayebi M, Shafipour G. Management of waste electrical and electronic equipment based on circular economy strategies: navigating a sustainability transition toward waste management sector. Clean Technol Environ Policy. 2021;23:343-69.

16. Oconnor MP, Zimmerman JB, Anastas PT, et al. A strategy for material supply chain sustainability: enabling a circular economy in the electronics industry through green engineering. ACS Sustain Chem Eng. 2016;4:5879-88.

17. Mazon MT, de Azevedo AMM, Pereira NM, et al. Does environmental regulation foster the diffusion of collaborative innovations? a study on electronics waste regulation on Brazil. Proc Soc Behav Sci. 2012;52:259-68.

18. Evans R, Vermeulen WJV. Governing electronics sustainability: Meta-evaluation of explanatory factors influencing modes of governance applied in the electronics value chain. J Clean Prod. 2021;278:122952.

19. Compagnoni M. Is extended producer responsibility living up to expectations? a systematic literature review focusing on electronic waste. J Clean Prod. 2022;367:133101.

20. Mihai FC. Paradigm shift in e-waste management, vision for the future. paradigm shift in e-waste management. CRC Press. 2022.

21. Marke A, Chan C, Taskin G, et al. Reducing e-waste in China's mobile electronics industry: the application of the innovative circular business models. Asian Educ Dev Stud. 2020;9:591-610.

22. Rimantho D, Syaiful S, Nurfaida, et al. Electronic waste bank model as a solution for implementing circular economy: case study DKI Jakarta-Indonesia. Front Built Environ. 2022;8:1030196.

23. Khan SAR, Tabish M, Yu Z. Investigating recycling decisions of internet recyclers: a step towards zero waste economy. J Environ Manag. 2023;340:117968.

24. Hunger T, Arnold M, Ulber M. Circular value chain blind spot – a scoping review of the 9R framework in consumption. J Clean Prod. 2024;440:140853.

25. Cordova-Pizarro D, Aguilar-Barajas I, Rodriguez CA, et al. Circular economy in Mexico's electronic and cell phone industry: recent evidence of consumer behavior. Appl Sci. 2020;10:7744.

26. Fröhlich P, Lorenz T, Martin G, et al. Valuable metals—recovery processes, current trends, and recycling strategies. Angew Chem Int Ed. 2017;56:2544-80.

27. Sureshkumar S, Rani PK, Agash CP, et al. Augmented reality and waste reduction: enhancing the recycling process for mobile e-waste in automotive manufacturing. 9th International Conference on Advanced Computing and Communication Systems, Coimbatore, India, 2023.

28. Senna P, Marujo LG, da Cunha Reis A, et al. Circular e-waste supply chains' critical challenges: an introduction and a literature review. Conversion of Electronic Waste in to Sustainable Products. 2022:233-250.

29. Velvizhi G, Shanthakumar S, Das B, et al. Biodegradable and non-biodegradable fraction of municipal solid waste for multifaceted applications through a closed loop integrated refinery platform: paving a path towards a circular economy. Sci Total Environ. 2020;731:138049.

30. Tong X, Wang T, Chen Y, et al. Towards an inclusive circular economy: quantifying the spatial flows of e-waste through the informal sector in China. Resour Conserv Recycl. 2018;135:163-71.

31. Hasan M, Plamthottathil RK, Morshed J, et al. Circulogy: an ai-enabled blockchain-based e-waste management framework using Non- Fungible Tokens (NFT) to achieve net zero and imply the circular economy. IEEE International Conference on Blockchain and Cryptocurrency. Ubai, United Arab Emirates. 2023.

32. Joshi S, Sharma M, Barve A. Implementation challenges of blockchain technology in closed-loop supply chain: a Waste Electrical and Electronic Equipment (WEEE) management perspective in developing countries. Supply Chain Forum: An Int J. 2023;24:59-80.

33. Yazdi M, Moradi R, Nedjati A, et al. E-waste circular economy decision-making: a comprehensive approach for sustainable operation management in the UK. Neural Comput Appl. 2024;36:13551-77.

34. De-Oliveira-Neto GC, De Jesus Cardoso Correia A, Tucci HNP, et al. Reverse chain for electronic waste to promote circular economy in Brazil: a survey on electronics manufacturers and importers. Sustainability. 2023;15:4135.

35. Pan X, Wong CWY, Li C. Circular economy practices in the Waste Electrical And Electronic Equipment (WEEE) industry: a systematic review and future research agendas. J Clean Prod. 2022;365:132671.

36. Cordova-Pizarro D, Aguilar-Barajas I, Romero D, et al. Circular economy in the electronic products sector: material flow analysis and economic impact of cellphone e-waste in Mexico. Sustainability. 2019;11:1361.

37. Althaf S, Babbitt CW, Chen R. Forecasting electronic waste flows for effective circular economy planning. Resour Conserv Recycl. 2019;151:104362.

38. Senna P, Marujo LG, Ferreira AC, et al. E-waste supply chain risk management: a framework considering the omnichannel and circular economy. Benchmarking: An Int J. 2023;31:3429-58.

39. Della-Bella S, Sen B, Cimpan C, et al. Exploring the impact of recycling on the demand-supply balance of critical materials in green transition: a dynamic multi-regional waste input-output analysis. Environ Sci Technol. 2023;57:10221-30.

40. Ibanescu D, Cailean D, Teodosiu C, et al. Assessment of the waste electrical and electronic equipment management systems profile and sustainability in developed and developing European Union countries. Waste Manag. 2018;73:39-53.

41. Constantinescu A, Platon V, Surugiu M, et al. The influence of eco-investment on e-waste recycling-evidence from EU countries. Front Environ Sci. 2022;10:928955.

42. Kurniawan TA, Lo W, Singh D, et al. A societal transition of MSW management in Xiamen (China) toward a circular economy through integrated waste recycling and technological digitization. Environ Pollut. 2021;277:116741.

43. Fawole AA, Orikpete OF, Ehiobu NN, et al. Climate change implications of electronic waste: strategies for sustainable management. Bulletin of the National Research Centre. 2023;47:147.

44. Salviulo G, Lavagnolo MC, Dabalà M, et al. Enabling circular economy: the overlooked role of inorganic materials chemistry. Chem Eur J. 2021;27:6676-95.

45. Kaya M, Tita AM. Electronic waste recycling in maintaining a circular economy. Electronic Waste Manag. 2023:301-316.

46. Islam MT, Huda N, Baumber A, et al. Waste battery disposal and recycling behavior: a study on the Australian perspective. Environ Sci Pollut Res. 2022;29:58980-9001.